

# Indications for an Extra Neutral Gauge Boson in Electroweak Precision Data

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A new analysis of the hadronic peak cross section at LEP 1 implies a small amount of missing invisible width in  $Z$  decays, while the effective weak charge in atomic parity violation has been determined recently to 0.6% accuracy, indicating a significantly negative  $S$  parameter. As a consequence of these two deviations, the data are described well if the presence of an additional  $Z'$  boson, such as predicted in Grand Unified Theories, is assumed. Moreover, the data are now rich enough to study an arbitrary extra  $Z'$  boson and to determine its couplings in a model independent way. An excellent best fit to the data is obtained in this case, suggesting the possibility of a family non-universal  $Z'$  with properties similar to ones predicted in a class of superstring theories.

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Neutral gauge structures beyond the photon and the  $Z$  boson have long been considered as one of the best motivated extensions of the Standard Model (SM) of electroweak interactions. They are predicted in most Grand Unified Theories (GUTs) and appear copiously in superstring theories. Moreover, in the context of supersymmetry, they do not spoil the observed approximate gauge coupling unification (as predicted by the simplest and most economic of these theories); in many models (but not the simplest  $SO(10)$  ones), the enhanced  $U(1)'$  gauge symmetry forbids an elementary bilinear Higgs  $\mu$ -term, while allowing an effective  $\mu$  to be generated at the scale of  $U(1)'$  breaking without introducing cosmological problems [1]. In many string-motivated models of radiative breaking, this scale is comparable to the electroweak scale (i.e., less than a TeV) [1], thus providing a solution to the  $\mu$ -problem [2], and enhancing the prospects to possibly detect it in high energy collisions or to find its effects on electroweak precision data. Yet, neither searches at the Tevatron [3], nor recent analyses of precision data [4,5], yielded evidence for the extra neutral  $Z'$  boson associated with the  $U(1)'$ , and stringent bounds on its masses and mixings were set.

Following the publication of our recent analysis [4] the contributions of  $\mathcal{O}(\alpha^3)$  to initial state radiation have been incorporated into the  $Z$  lineshape analysis at LEP and the theoretical luminosity uncertainty reduced. The new  $Z$  lineshape fit [6] (which includes new experimental input, as well) yields a significantly larger and more precise value for the hadronic peak cross section,  $\sigma_{\text{had}}$ , implying, e.g., for the effective number of massless neutrinos,  $N_\nu = 2.985 \pm 0.008$ , which is  $2\sigma$  below the prediction of 3 standard neutrinos. Therefore, the data favors types of

new physics which can mimic a negative contribution to the invisible  $Z$  decay width.

The effective weak charge,  $Q_W$ , in atomic parity violation can be interpreted as a measurement of the  $S$  parameter, with very little sensitivity to the other oblique parameters,  $T$  and  $U$ , all of which parametrize new physics effects due to vector boson self-energies [7]. Extra  $Z$  bosons are not of the pure oblique type, but in the absence of new contributions to the  $\rho_0$  parameter (or equivalently to  $T$ ) they mimic  $S < 0$  if the boson masses satisfy  $M_{Z'} > M_Z$  [8]. The  $Q_W$  determination for Cs [9] has been improved recently to the 0.6% level by measuring the ratio of the off-diagonal hyperfine amplitude (which is known precisely [10]) to the tensor transition polarizability [11]. As a result, the theory uncertainty was reduced significantly and the new  $Q_W(\text{Cs}) = -72.06 \pm 0.44$  is found to be  $2.3\sigma$  above the SM prediction.

These two developments necessitate the present update of our analysis in Ref. [4], partly reversing our previous conclusions. The fit to the new precision data improves upon the introduction of certain  $Z'$  bosons, among them the  $Z_\chi$ , defined by  $SO(10) \rightarrow SU(5) \times U(1)_\chi$ . Most of the utilized data were presented at the International Europhysics Conference on High Energy Physics at Tampere. For more details and references we refer to the update in Ref. [12]. Our analysis is based on the FORTRAN routines GAPP [14] including a minor update: for the model-independent fits it is important to express the hadronic charge asymmetry directly in terms of the  $Z$  width ratios,  $R_q \equiv \Gamma(q\bar{q})/\Gamma(\sum_q q\bar{q}) \equiv \Gamma(q\bar{q})/\Gamma(\text{had})$ , and the forward-backward asymmetries,

$$Q_{FB} = \left( \sum_{q=d,s,b} - \sum_{q=u,c} \right) R_q A_{FB}^{(q)} = 0.04092 \pm 0.00226.$$

The  $U(1)'$  coupling,  $g' = \sqrt{5/3} \sin \theta_W \sqrt{\lambda} g_Y$ , is defined in terms of the hypercharge ( $Y$ ) gauge coupling,  $g_Y$ , and the weak mixing angle,  $\theta_W$ , such that  $\lambda = 1$  if the GUT group breaks directly to  $SU(3) \times SU(2) \times U(1)_Y \times U(1)'$ .  $\lambda = 1$  will be assumed throughout, but our limits also apply to  $\sqrt{\lambda} \sin \theta$  and  $\frac{M_{Z'}}{\sqrt{\lambda}}$  for other values of  $\lambda$  (we always assume  $M_{Z'} \gg M_Z$ ). Since the  $U(1)_\chi$  and  $U(1)_Y$  are orthogonal at the GUT scale, their kinetic mixing term,  $F'_{\mu\nu} F^{\mu\nu}$ , is small in minimal models. We also assume  $\rho_0 = 1$ , i.e., only Higgs doublets and singlets receive vacuum expectation values (VEVs). The  $Z_\chi$  model has then only  $M_{Z'}$  and the  $Z - Z'$  mixing angle,

$$\tan^2 \theta = \frac{M_0^2 - M_Z^2}{M_{Z'}^2 - M_0^2}, \quad (1)$$

TABLE I.  $U(1)'$  charges of a **27** representation for an arbitrary  $E_6$  boson. Proper  $E_6$  normalization is obtained by dividing by  $2\sqrt{4a/3 + 5b/3 + ab + 10/9 + a^2 + 4b^2}$ . The upper half of the Table with  $b = 0$  corresponds to a family in  $SO(10)$  GUT.  $a = 0$  describes the  $E_6$  boson in the absence of kinetic mixing.  $D$  ( $\bar{D}$ ) are exotic (anti)-quarks, while the other new states are color singlets.

$\begin{pmatrix} \nu \\ e^- \end{pmatrix}$	-1		$\bar{\nu}$	+5/3	+a	+2b
			$e^+$	+1/3	-a	+b
$\begin{pmatrix} u \\ d \end{pmatrix}$	+1/3	+b	$\bar{u}$	+1/3	+a	+b
			$\bar{d}$	-1	-a	
$\begin{pmatrix} N \\ E^- \end{pmatrix}$	+2/3	+a	-b	$D$	-2/3	-2b
				$\bar{D}$	+2/3	-b
$\begin{pmatrix} E^+ \\ \bar{N} \end{pmatrix}$	-2/3	-a	-2b	$S$	0	+3b

as new parameters, where  $M_0$  is the mass of the ordinary  $Z$  in the absence of mixing. The resulting fit,

$$M_{Z'} = 812_{-152}^{+339} \text{ GeV}, \quad \sin \theta = (-1.12 \pm 0.80) \times 10^{-3},$$

$$M_H = 145_{-61}^{+103} \text{ GeV}, \quad \alpha_s = 0.1233 \pm 0.0039,$$

suggests a TeV scale  $Z'$  with small mixing. The lower  $\chi^2_{\min} = 35.35$  for 35 degrees of freedom (d.o.f.) compared with the SM ( $\chi^2_{\min}/\text{d.o.f.} = 41.88/37$ ) is mostly due to the improvement in the predictions for the atomic parity observables ( $\Delta\chi^2 = -5.67$ ), but also in  $\sigma_{\text{had}}$  ( $\Delta\chi^2 = -2.34$ ). There is little change in the ratios,  $R_\ell = \frac{\Gamma(\text{had})}{\Gamma(\ell^+\ell^-)}$  ( $\ell = e, \mu, \tau$ ), and the other observables, except that the total  $Z$  width,  $\Gamma_Z$ , and the  $W$  mass,  $M_W$ , each contribute about 0.7 more to the total  $\chi^2$ . The improvement in  $\sigma_{\text{had}}$  is subtle: the  $Z_\chi$  causes the total and all partial  $Z$  decay widths to increase, with the exception of the invisible width which decreases by about 0.7 MeV. Hence,  $\Gamma(\text{had})$  increases more (1.66 MeV) than  $\Gamma_Z$  (1.15 MeV), implying an overall increase in  $\sigma_{\text{had}} = \frac{12\pi}{M_Z^2 R_e} \frac{\Gamma(\text{had})^2}{\Gamma_Z^2}$ . As can be seen from the fit result, the relatively large increase in  $\Gamma(\text{had})$  is caused by an increased value for  $\alpha_s$  (SM:  $\alpha_s = 0.1192 \pm 0.0028$ ), in better agreement with expectations from supersymmetric GUT. At the same time, the  $Z_\chi$  does not affect the preference for a light Higgs, again in agreement with supersymmetry. The value of  $\alpha_s$  is, however, slightly higher than the current world average,  $\alpha_s = 0.1182 \pm 0.0013$  [15], from determinations excluding the  $Z$  lineshape. Including this value as an additional external constraint yields a result consistent with vanishing  $Z - Z'$  mixing,  $\sin \theta = (-0.46 \pm 0.60) \times 10^{-3}$ , and a smaller decrease in  $\chi^2_{\min}/\text{d.o.f.} = 36.85/36$  (SM:  $\chi^2_{\min}/\text{d.o.f.} = 42.00/38$ ). The characteristics of this fit are different than the one before: there is a smaller increase in  $\Gamma(e^+e^-)$  (0.03%) and there is now a small decrease in  $\Gamma_Z$  (-0.01%), while  $\Gamma(\text{had})$  is virtually unchanged. As a result  $\sigma_{\text{had}}$  is still in better agreement than in the SM, but at the expense of larger discrepan-

TABLE II. Examples of  $Z'$  bosons inspired by  $E_6$  symmetry. The  $Z_\eta$  occurs in Calabi-Yau compactifications of the heterotic string if  $E_6$  breaks directly to a rank 5 subgroup [19] via the Hosotani mechanism. The  $Z_\eta^*$  does not couple to leptons and was originally introduced to explain a temporarily observed excess of  $b$  quark events at LEP [20]. For the  $Z_{LR}$ , the values in parentheses are for  $g_L = g_R$ ; also assumed for the alternative LR model [21],  $Z_{ALR}$ , which changes the fermion assignment, viz.  $(\nu, e^-) \leftrightarrow (N, E^-)$ ,  $\bar{d} \leftrightarrow \bar{D}$ , and  $\bar{\nu} \leftrightarrow S$ .

$Z'$	$a$	$b$	$\sin \alpha$	$\tan \beta$
$-Z_\chi$	0	0	0	0
$Z_Y$	-5/3	0	-1	0
$Z_{B-L}$	-2/3	0	$-\sqrt{2/5}$	0
$-Z_{LR} > -5/3$ (1.66)		0	$< \sqrt{3/5}$ (0.52)	0
$Z_{ALR}$	-0.71	-0.48	-0.93	1.47
$-Z_\psi$	0	-4/3	0	$-\infty$
$-Z_\eta$	0	5/3	0	$-\sqrt{5/3}$
$-Z_\eta^*$	$\infty$	$a$	$\sqrt{8/35}$	$-3/\sqrt{7}$

cies in  $R_e$  ( $1.5\sigma$ ) and  $R_\mu$  ( $1.7\sigma$ ). Recalling that most of the  $\alpha_s$  determinations are dominated by theoretical uncertainties, it is clearly important to verify the very tight (and intrinsically non-Gaussian) constraint on  $\alpha_s$ , which we believe to be asymmetric with a larger positive error.

If the Higgs  $U(1)'$  quantum numbers,  $Q'_i$ , are known, there will be an extra constraint,

$$C = \theta \frac{g_Y}{g'} \frac{M_{Z'}^2}{M_Z^2} = - \frac{\sum_i t_{3i} Q'_i |\langle \phi_i \rangle|^2}{\sum_i t_{3i}^2 |\langle \phi_i \rangle|^2}, \quad (2)$$

where the  $\langle \phi_i \rangle$  are VEVs, and  $t_{3i}$  is the third component of isospin. For minimal cases it is given explicitly in Table III of Ref. [16]. In particular, in  $SO(10)$  with light Higgs fields from the fundamental **10** representation,  $C = 2/\sqrt{10}$  is predicted, and therefore  $\theta \sim 5 \times 10^{-3} > 0$ . This Higgs structure is strongly disfavored by our results.

In the  $Z_\chi$  model there is no need to introduce exotic fermions beyond the right-handed neutrino. The question arises what are the most general  $Z'$  couplings consistent with generation-wise cancellation of gauge and mixed gauge-gravitational anomalies. The solution can be parametrized by the  $Z_\chi$  couplings plus a shift proportional to the right-handed isospin generator,  $-2aI_R^3$ . A non-zero kinetic mixing term [17] cannot affect the consistency of the theory, and is therefore equivalent to this shift. Also any  $U(1)'$  originating from an  $SO(10)$  GUT can be described by  $a$ . For example, the  $Z'$  appearing in left-right (LR) models corresponds to  $a = g_R^2/g_L^2 \cot^2 \theta_W - 5/3$ . A fit with  $a$  yields  $a \geq -0.50$  and,

$$M_{Z'} = 781_{-241}^{+362} \text{ GeV}, \quad \sin \theta = (1.23 \pm 0.89) \times 10^{-3},$$

$$M_H = 165_{-91}^{+155} \text{ GeV}, \quad \alpha_s = 0.1239 \pm 0.0045,$$

with  $\chi^2_{\min}/\text{d.o.f.} = 35.26/34$ . The 95% CL ( $\Delta\chi^2 = 3.84$ ) constraint  $a \geq -0.81$  implies for the LR model  $g_R \geq 0.51 g_L$ , to be compared with the consistency requirement

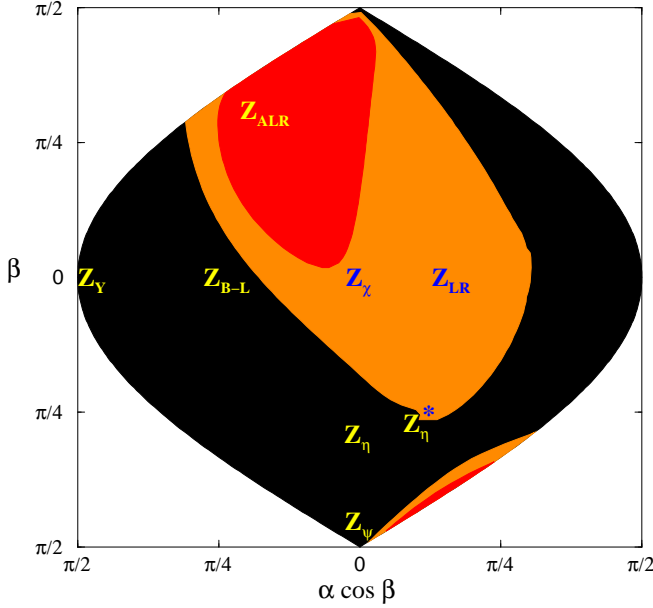


FIG. 1. Sinusoidal (Sanson-Flamsteed) projection of a hemisphere parametrizing arbitrary  $E_6$  inspired  $Z'$  models. Distances along constant  $\beta$ , the central meridian, and area are preserved. Shown are the  $1\sigma$  and 90% ( $\Delta\chi^2 = 3.04$ ) contours allowed by the data. Note, that while the  $Z_\psi$  model (mapped to the poles) does not improve the prediction for  $Q_W$ , it gives a very good fit if some kinetic mixing is allowed.

$g_R \geq 0.55 g_L$  [18] from the  $W'$  sector of these models. The LR symmetric case,  $g_R = g_L$ , yields a lower range for  $\alpha_s = 0.1210 \pm 0.0032$ , and  $\chi^2_{\min}/\text{d.o.f.} = 36.05/35$ .

The  $E_6$  group contains also a purely axial-vector  $Z_\psi$  boson, defined through  $E_6 \rightarrow SO(10) \times U(1)_\psi$ . We define the most general  $E_6$  boson as a linear combination of the  $SO(10)$  boson (parametrized by  $a$ ) and the  $Z_\psi$ , via introduction of a second parameter,  $b$ . Alternatively,

$$Z' \sim -\cos \alpha \cos \beta Z_\chi + \sin \alpha \cos \beta Z_Y - \sin \beta Z_\psi, \quad (3)$$

can be expanded in terms of an orthonormal basis, with

$$\begin{aligned} a &= \frac{-\sin \alpha}{\frac{3}{5} \sin \alpha - \sqrt{\frac{27}{50}} \cos \alpha - \sqrt{\frac{1}{10}} \tan \beta}, \\ b &= -\sqrt{\frac{8}{45}} \frac{\tan \beta}{\sin \alpha} a. \end{aligned} \quad (4)$$

The couplings of the states in the **27** are listed in Table I. The angles  $\alpha$  and  $\beta$  parametrize the surface of a sphere where opposite points correspond to the same model with the opposite sign of  $\theta$ . Therefore, we can restrict ourselves to one hemisphere defined by  $-\pi/2 \leq \alpha, \beta < \pi/2$ . The values of the parameter sets  $(a, b)$  and  $(\alpha, \beta)$  are shown for popular cases in Table II. A fit with both  $a$  and  $b$  allowed yields  $\chi^2_{\min}/\text{d.o.f.} = 34.21/33$ , and

$$M_H = 131^{+131}_{-64} \text{ GeV}, \quad \alpha_s = 0.1232^{+0.0050}_{-0.0046}.$$

The  $1\sigma$  contour and the 90% CL allowed region obtained by integrating over the hemisphere (giving each point

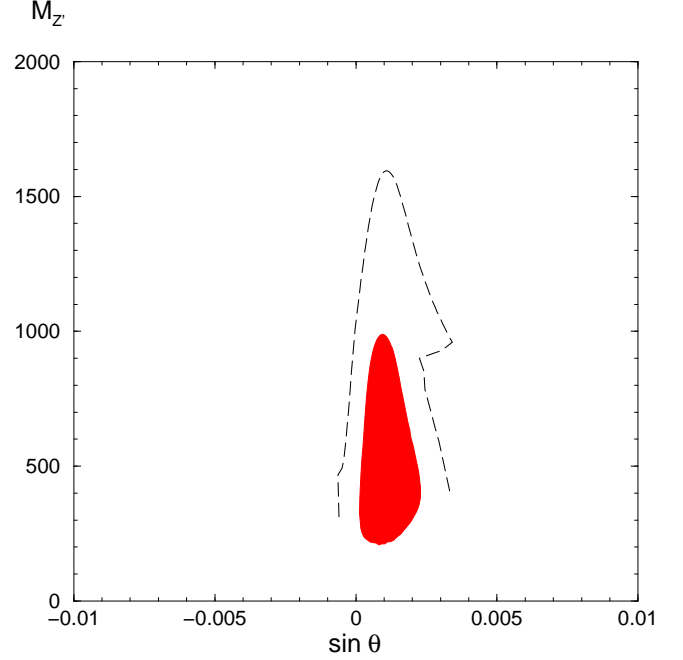


FIG. 2.  $M_{Z'}$  as a function of  $\sin \theta$  for an arbitrary  $E_6$  inspired  $Z'$ . The contours correspond to the ones in Fig. 1.

equal prior probability) is shown in Fig. 1. The corresponding contours in  $M_{Z'}$  vs.  $\sin \theta$  are shown in Fig. 2. The  $1\sigma$  contour in Fig. 1 shows that  $a$  is consistent with zero, while  $b < 0$ . If we repeat this fit with  $a = 0$  fixed (no kinetic mixing), we find  $\alpha_s = 0.1216 \pm 0.0036$  closer to the outside constraint. Including it in the fit yields

$$\begin{aligned} M_{Z'} &= 287^{+673}_{-101} \text{ GeV}, & \sin \theta &= (0.36 \pm 0.63) \times 10^{-3}, \\ M_H &= 101^{+57}_{-39} \text{ GeV}, & \alpha_s &= 0.1186 \pm 0.0012, \\ b &= -1.06^{+0.91}_{-0.16}, & \chi^2_{\min}/\text{d.o.f.} &= 35.58/35. \end{aligned}$$

This concludes our discussion of  $E_6$  bosons, which constitute a very well motivated class of cases, both in GUT and superstring contexts, and many of which significantly improve the fit to the precision data.

A family-universal  $Z'$  with otherwise arbitrary couplings is described by the five charges of the SM multiplets (cf. Table I), and the mixing angle,  $\theta$ .  $M_{Z'}$  cannot be determined independently using the precision data, and will be fixed to 1 TeV in the following (for other values the charges and mixing scale as  $M_{Z'}$  and  $M_{Z'}^{-1}$ , respectively). We also employ the  $\alpha_s$  constraint [15], as otherwise the strong coupling is driven to very low and clearly excluded values. The resulting fit is good,  $\chi^2_{\min}/\text{d.o.f.} = 31.73/32$ , and yields the couplings,

$$\begin{aligned} (\nu, e)_L &= -0.24^{+0.12}_{-0.23}, & e_R &= -0.21^{+0.12}_{-0.14}, \\ (u, d)_L &= -0.16^{+0.30}_{-0.92}, & d_R &= 1.32^{+1.35}_{-0.51}, \\ \sin \theta &= (4.04^{+0.69}_{-2.72}) \times 10^{-3}, & u_R &= 0.05^{+1.22}_{-0.67}. \end{aligned}$$

Stronger mixing is allowed than in the  $E_6$  cases, and we find the 95% CL bound,

$$|\sin \theta \frac{M_{Z'}}{1 \text{ TeV}}| \leq 5.31 \times 10^{-3}, \quad (5)$$

mainly from  $M_W$ . The leptonic couplings,  $e_L \approx e_R$ , as well as  $d_R$  and  $\theta$ , all are significantly different from zero and strongly correlated. In contrast to the  $E_6$  inspired cases, the tendency for a light Higgs is lost; instead we find  $M_H \geq 210$  GeV for the  $1\sigma$  ranges above. Another family-universal possibility is the sequential  $Z_{\text{SM}}$ , with the same couplings as the  $Z$ . For example, this could be due to the excited  $Z$  states in models with extra TeV-scale dimensions. However, the  $Z_{\text{SM}}$  would yield a *larger*  $|Q_W(\text{Cs})|$ , increasing the discrepancy with experiment.

In general, the extra  $Z$  boson may not couple in a universal way. There are, however, strong constraints from flavor changing neutral current processes specifically limiting non-universality between the first two generations. On the other hand, the third generation is less constrained. We therefore treat the first two generations as universal, while allowing arbitrary couplings to the third. Since the  $U(1)'$  charge of the top quark does not enter (at tree level), there are four new parameters compared to the universal fit; we find,

$$\begin{aligned} (\nu, e)_L &= -0.32^{+0.13}_{-0.69}, & (\nu, \tau)_L &= -0.24^{+0.78}_{-0.57}, \\ e_R &= -0.31^{+0.13}_{-0.60}, & \tau_R &= 0.03^{+1.92}_{-0.25}, \\ (u, d)_L &= -0.52^{+1.11}_{-4.78}, & (t, b)_L &= 1.32^{+9.10}_{-0.72}, \\ d_R &= 1.72^{+5.61}_{-1.25}, & b_R &= 8.48^{+52.4}_{-3.16}, \\ u_R &= 0.38^{+4.85}_{-1.18}, & \sin \theta &= (4.06^{+0.69}_{-3.51}) \times 10^{-3}, \end{aligned}$$

and an excellent  $\chi^2_{\text{min}}/\text{d.o.f.} = 25.33/28$ , while the bound (5) is virtually unchanged. Six of the ten quantities are significantly different from zero, and all couplings are of similar magnitude and  $\mathcal{O}(1)$  (for a TeV scale  $Z'$ ), except for  $b_R$  which appears surprisingly large (driven by the experimental anomaly in the asymmetry parameter  $A_b$  at LEP and SLC). It is amusing, however, that  $b_R/u_R = 22.62$  is consistent with the prediction (22.67) of a closely investigated superstring model [22,23] (based on the fermionic construction of the heterotic string). Of course, some other predictions fail, but it is important to keep in mind that unlike in GUT models, superstrings often predict family non-universal  $Z'$  bosons with highly unconventional coupling ratios. The  $\chi^2_{\text{min}}$  is lower by  $-16.67$  for 10 d.o.f. as compared to the SM, which has a probability of 8.2% to be due to a fluctuation.

We therefore conclude, that the data are generally better described if the presence of an extra  $Z'$  boson is assumed. There are many realizations of such a possibility, ranging from the standard and much more restrictive GUT scenarios to the more exotic bosons as predicted in some string models. Of course, a light  $Z'$  precludes a heavy Majorana neutrino, as is invoked in seesaw models and some models of baryogenesis, except in the cases that the neutrino (e.g.,  $\bar{\nu}$  or  $S$  in Table I) carries no  $U(1)'$  charge. A  $Z'$  with mass  $\lesssim 1$  TeV may be directly observable by its leptonic decays in Run II at the Tevatron, and

certainly at the LHC. For this mass range, a variety of complementary diagnostics of its couplings will be possible at the LHC, a future lepton collider, as well as from the precision data [1,24].

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